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Soil chemical properties of silvoarable agroforestry systems of the Czech Republic

Diploma thesis

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Abstract:

Aim of this thesis was evaluation of influence of introduction of Agroforestry practises in agricultural landscape of Central Europe on content of organic carbon in soil. Agroforestry practises are very potential tool for increasing environmental stability and biodiversity. Also very promising is its capability of carbon sequestration as instrument of climate change mitigation. Study found that woody perennial elements in agroforestry system (AFS) can accumulate higher amount of soil organic carbon (SOC) than rest of the AFS. Comparison of arable part of AFS with a conventional field wasn't significant.

Abstract

Cílem práce bylo zhodnotit vliv zavádění agrolesnických postupů v zemědělské krajině Střední Evropy na obsah organického uhlíku v půdě. Agrolesnické postupy jsou slibným nástrojem pro zlepšování environmentální stability a biodiversity. Velmi slibná je také jejich schopnost sequestrovat uhlík, jako nástroj mitigace klimatické změny. Studie zjistila, že trvalé dřivny v agrolesnických systémech (AFS) akumulují vice půdního organického uhlíku (SOC) než ostatní části AFS. Srovnání oraných částí AFS s běžně obhospodařovaným polem nepřineslo signifikantní výsledky.

Content

1. Introduction

Agroforestry systems (AFS) are agricultural/landscape management practises, which are currently rediscovered in conditions of Central Europe. This methods of land use, that are characteristic by integration of wood perennials into standard farm practises are still common in tropical and subtropical agroforestry. Implementing of trees on arable soil could provide production advantage and also many non-productive benefits like protection of soil or CO_2 sequestration, which may be very important aspect of climate change mitigation. On this promising ability of AFS aiming this study.

Current form of intensive agricultural has many connections with global change and emissions of greenhouse gases. Its only logical, that solutions, which aim on a source of the problem, will be very effective.

Environmental improvement of whole landscape and especially soils while, at least minimize production losses, will be key for sustainable existence worldwide. Agroforestry practises are potential tool. Good examples of successful use could be found in equatorial belt or even in our own history of landscape maintenance.

The purpose of this thesis is contribute to understanding the role of organic carbon in soil and possibility of its sequestration under different condition of management.

2. Scientific objectives and hypotheses of work

The aim of this work is to evaluate impact of the adoption of agroforestry on soil properties with a special emphasis on soil carbon storage. Research focused on the evaluation of spatial distribution of soil organic carbon (SOC) within soil profile in dependence of the distance from the woody perennial in two alley cropping agroforestry systems in the Czech Republic and its comparison to the adjacent conventional agricultural land. To better understand the dynamics of C turnover in soil, we selected two alley cropping systems with different history: one established on agricultural land by planting trees on arable land (Šardice area), and one by removing trees from previous long-term tree nursery creating tree lines and open field alleys (Průhonice area).

We hypothesized that the presence of woody perennials within agriculturally managed land enhances the C concentration in soil. Specifically, we assume that:

(i) Woody perennials increase SOC in the top soil layer due to the great amount of litterfall

(ii) Woody perennials increase the SOC in the deeper soil layers due to the high concentration of root exudates and turnover, as well as due to the absence of the tillage under the trees.

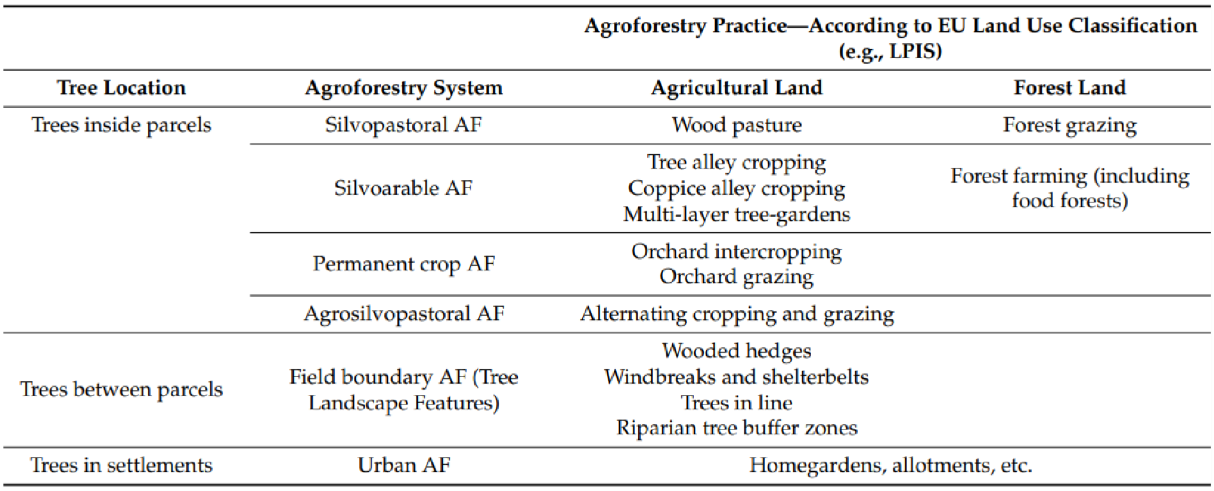
(iii) We expect a trend of SOC concentration reduction with the increasing distance from trees in both study areas: while in Průhonice this is caused by the enhanced SOC oxidation in the alleys by tillage, the newly established tree lines in Šardice start the slow SOC build-up.

3. Literature Review

3.1. Agroforestry

3.1.1. Introduction to AFS

Agroforestry systems (AFS) is designation of wide scale of agricultural systems, which combine regular crop production and/or livestock grazing with inclusion of woody species. The purpose of these practises is alignment of single elements, which could possibly act even in an antagonistic way, to synergistically acting unit (Martiník et. al. 2013). Environmental benefits are obvious, however despite the presence of woody plants, agroforestry systems lack diversification, density, and structural complexity typical of natural ecosystems (Guo & Giford 2002).



		Agroforestry Practice—According to EU Land Use Classification (e.g., LPIS)	
Tree Location	**Agroforestry System**	**Agricultural Land**	**Forest Land**
Trees inside parcels	Silvopastoral AF	Wood pasture	Forest grazing
	Silvoarable AF	Tree alley cropping Coppice alley cropping Multi-layer tree-gardens	Forest farming (including food forests)
	Permanent crop AF	Orchard intercropping Orchard grazing	
	Agrosilvopastoral AF	Alternating cropping and grazing	
Trees between parcels	Field boundary AF (Tree Landscape Features)	Wooded hedges Windbreaks and shelterbelts Trees in line Riparian tree buffer zones	
Trees in settlements	Urban AF	Homegardens, allotments, etc.	

Table 1. Agroforestry systems and practises proposed by EURAF (European Agroforestry Federation) (Lojka et. al. 2022)

Globally, an estimated 700, 100, 300, 450, and 50 Mha of land are used for tree intercropping, multistrata systems, protective systems, silvopasture, and tree woodlots, respectively (Nair 2012).

In fact, agricultural methods are very old. Original forms of farming worldwide, could be probably called agroforestry very easy (partly due to somewhat broad definition of this term).

One of the simplest way to transform forest or forest-steppe (i.e. the most likely, common landscape types in central Europe before Anthropocene) into arable land, is let a cattle to graze-of bushes and small trees. Similar practise, so called forest pasture was common in most of Europe until modern age, when it was baned due to forest protection. The most typical form was pig grazing in oak stands. Other example is special form of ancient field structure, in czech called „Plužiny“, in german „-flur“, which could, at first sight, be considered as silvoarable land or, at least as robust windbreak system (Konšel et. al. 1940; Nožička 1957).

Usual, maybe even traditional way of land management in central Europe, with practically untranslatable name „polaření“, use forest clearings for periodical agricultural production. This practise is typical for it´s „virtue out of necessity“ character, which is symptomatic for most of these, often massively promoted land management methods, which were forgotten mostly in the beginning of twentieth century, due to technological advances. „Polaření“ was common in highly afforested regions, with lack of arable land or even pastures. Clear cutting of high forest created free area, that was used (or rather exploit) for farming, for a period of 1-3 years. Forest soils are generally of relative poor fertility, but in rapidly changed condition of light, temperature and humidity regime, these lands could provide decent amount of nutrients, by accelerated decomposition of accumulated tree litter. This was enough for undemanding species like rye, oat or millet. Very poor sites were used just for fodder production or grazing. In conclusion, just small terminological detail, this specific kind of agriculture is probably most suitable for term „agroforestry“, due it´s obvious connection with silviculture, unlike in other types, which are just about using woody perennials in farming (Konšel et. al. 1940).

Perception of these methods vary. On one hand, this was very effective „motivation“ for workers in hunger-for-land times, taking care of forest restocking was usually a condition for tenancy. If agricultural using continue simultaneously with reforesting, by intercropping between row of planting, it helps with weed control. On the other, this practises could deplete soil nutrients, which are already quite limited in forest soils. However, with favourable management (i.e. growing legumes, rich input of plant residues, etc.), this could lead to condition improvement (Konšel et. al. 1940; Nožička 1957).

3.1.2. Ecology of AFS

Compared to monocultures, AFS are more efficient in capturing the resources available at the site for biomass growth and the increased growth may result in higher C inputs to the soil. Also, direct C inputs to the soil can potentially be increased by some agroforestry practices like returning remains of prunings in form of mulch and tree litter to the soil or allowing livestock to graze and add dung (Lorenz & Lal 2005; Nair et. al. 2010). In contrast, thinning and pruning of trees may reduce SOC sequestration by reducing litter fall and accelerating decomposition due to changes in understory light, air/soil temperature, and soil moisture regimes (Jandl et al. 2014). Perennial grasses present in AFS seem to be more efficient than woody plants in storing C in soil. Trees deposit a larger fraction of organic matter on the soil surface than grasses, thus intensify process of decomposition, which might lead to less formation of SOM and consequently less SOC (Guo and Gifford 2002).

Generally, agroforestry reduce tillage and soil disturbance regimes, which can help to maintain or even increase SOC pools (Aslam et. al. 1999). These land management practises have a higher potential to sequester atmospheric CO_2 than the croplands, pastures, or natural grasslands, i.e., treeless land uses they replace, but effects on SOC vary greatly depending on biophysical and socioeconomic characteristics of the system parameters (Nair et. al. 2009). Trees modify the quality and quantity of belowground litter C inputs and modify microclimatic conditions such as soil moisture and temperature regimes (Laganière et al. 2010). In temperate regions, afforestation of former cropland caused a long-lasting SOC sink but the majority of afforested grasslands lost SOC (Poeplau et al. 2011). Whether mechanisms of SOM stabilization and destabilization can potentially be affected by agroforestry practices is less well known, although practices that promote the depth transfer of SOM may result in higher profile SOC pools as decomposition is slower and the proportion of stabilized SOM is higher in deeper soil layers (Lorenz & Lal 2005). Broadleaf tree species have a greater capacity to enhance SOC pool, most probably due to their higher root biomass-to-aboveground biomass ratio than conifer trees (Laganiére et al. 2009).

Root litter usually decomposes more slowly than leaf litter of the same species (Cusack et al. 2009). Fresh root inputs may also ‘prime’ microbial activity, leading to faster decomposition of older organic matter as well as changing community composition (Kuzyakov 2010; Agren et al. 2001). Aside from deep soil C inputs, another reason for the promotion of SOC sequestration in agroforestry systems is, that tree roots have the potential to recover nutrients from below the crop rooting zone. The resulting enhanced tree and crop plant growth by subsequent increase in nitrogen nutrition may result in an increase in SOC sequestration (van Noordwijk et. al. 2006). Similar, mixed plantings with N-fixing trees may cause higher biomass production and, thus, SOC sequestration and pools particularly in deeper soil horizons as N may promote humification rather than decay (Nair et al. 2009). Also, changes in microbial decomposer community composition under N-fixing trees may result in greater retention of relatively stable SOC (Resh et al. 2002).

For example, the roots of wheat (*Triticum aestivum* Linn.) intercropped with jujube (*Ziziphus jujuba* Mill.) trees had more shallow distribution in the soil profile and smaller root length densities than mono-cropped wheat. In addition, the roots of intercropped jujube trees occupied a comparatively smaller soil space than sole-cropped trees. Decreased soil exploration and apparent root competition led to decreases in yield and biomass (Zhang et al. 2013).

Cereals (wheat and barley) transfer 20 % ± 30 % of total assimilated C into the soil. Half of this amount is subsequently found in the roots and about one-third in CO2 evolved from the soil by respiration and microbial utilization of organic sub-stances. The remaining part of below-ground translocated C is incorporated into the soil microorganisms and soil organic matter. The portion of assimilated C allocated below the ground by cereals decreases during growth and by increasing N fertilization.

Pasture plants translocated about 30%±50% of assimilates below-ground,and their translocation patterns were similar to those of crop plants. On average, the total C amounts translocated into the soil by cereals and pasture plants are approximately the same (1500 kg), when the same growth period is considered. However, during one vegetation period the cereals and grasses allocated beneath the ground about 1500 and 2200 kg C, respectively (Kuzyakov & Domanski 2000).

However, inventory data on root biomass are uncertain due to spatial and temporal heterogeneity, uneven sampling, and methodological differences among studies. The fine root turnover transfers a large fraction of net primary production into soil but published estimates on fine root turnover time differ more than fivefold which may also be the result in differences in methods (Guo et al. 2008).

Rhizodeposition describes the release of organic C compounds by roots. Most studies about finding the amount of C fixed by plant photosynthesis partitioned belowground have focused on young plants but partitioning strongly depends on plant age. Further, almost half of the published data are for wheat (*Triticum* spp.) and ryegrass (*Lolium* spp.), and 76 % of the studies are related to only five crop/grassland species. Thus, the knowledge of C rhizodeposition and specifically, those of mixed plant communities such as AFS is scanty. The rigorous quantification of C sequestration in AFS soils is problematic, due the fact that the amount of rhizodeposition by trees is virtually unknown (Jones et al. 2009).

Further, hydraulic lift of soil water by roots of a single tree may enhance soil water uptake by neighboring trees and other plants in the agroforestry system which may affect SOC sequestration due to an increase in productivity and accelerated decomposition (Liste & White 2008). Also, in surface soil horizons of intensively managed agricultural landscapes, trees potentially reduce SOC losses by reducing soil erosion (Lal 2005).

Nevertheles, understory species may be negatively affected by the tree presence, and trees and crops may compete for water (Burgess et al. 2005). Crucial could be position of allelopathic and disease vectors. Allelochemicals are present in many types of plants and are released into the soil by a variety of mechanisms (Jose et al. 2004). Awareness of phytotoxins or inhibitors, which plants exude is necessary for crop composition. Relation between these substances and environment vary, planted species can suppress or even kill each other but allelochemicals may also contribute to pest management, as some of them can act as natural biocides. Trees live long and produce a large amount of leaves and litter, so this effect can accumulate. Thus, species mixtures with no or positive allelopathic effects on the companion crops must be created in agroforestry systems. (Rizvi et al. 1999). However, allelopathic investigations in agroforestry systems are often lacking conclusive field verification. For example, separating allelopathic effects of trees from root competition is challenging (John et al. 2006).

Conclusions based on the observations of SOC changes by afforestation may be limited by inappropriate experimental design, sampling methods, and/or soil analysis techniques (Laganiére et al. 2009). Also, observed SOC sequestration rates are particularly highly variable and only a very limited number of field experiments have been specifically designed to rigorously test the effects of agroforestry practices on SOC (Lorenz & Lal 2014).

However, despite the presence of woody plants, agroforestry systems lack diversification, density, and structural complexity typical of natural ecosystems (Guo & Gifford 2002).

3.1.3. Influence of wood perennials on soil

The purpose of this part, was primarily demonstrate ambivalent impact of trees on soil chemistry and development. There is often strong accent on soil amelioration by influence of trees but this is relatively controversial. The majority of forest in central europe grows on land, which is, simply put incapable of cultivation due to terrain inaccessibility, high skeletal content, low fertility etc. These elements are cause of soil condition, which can be also result of plant species influence and vice versa (= species composition depends on site characteristics) (Konšel 1931; Poleno et. al. 2009).

A spine of czech forests is made by coniferous trees. Majority of them have relative acid litter, which act as almost inhibitor of most of organic activity in soil. Obviously, spruce, pine or larch are not suitable species for use on arable land (in fact, these wood plants are usually completely unfavourable for any purpose outside of forestry). The best ameliorative properties have birch, rowan, lime or hornbeam, further leaves of maple and ash are known for quite high content of bases (Kacálek et. al. 2017).

It should be noted, that majority of research, focused on effects of trees on soil chemistry were realised in silviculture context, so results based on replacement of coniferous trees on, often more or less degraded sites by species, which are at least site suitable, could be misleading for agricultural soils. In other worlds: if compared to influence of grass and legumes on soil development, effect of most of woody species could be even degrading (Kacálek et. al. 2017). But is necessary to say, that successful examples of SOC stock recovery after afforestation and reforestation are common in literature (Houghton 1995, Don et. al. 2011).

For ameliorative species is significant fast decomposability of leaf litter, which *inter alia* indicate good activity of edaphone but fast decay can also mean intensive mineralization of organic compounds and low fixation of carbon matter in soil (Kacálek et. al. 2017). Fast and intensive decomposition of large amount of dead mass usually leads to decrease of pH (intermediates of decay and following synthesis are organic acids and CO_2, which stimulates acidification) (Vlček et. al. 2020). On the contrary, a recalcitrant material could provide higher probability of carbon sequestration but can lead to accumulation of organic mass, which is not consider as favourable (Preston et. al. 2009).

Cause of persistence to decay of biomass could be complicated. Tree litter of spruce, pine, but also beech has a tendency to accumulation. Reason is relative acidity, as was mentioned above. Different cause of durability has wood mass, which is very poor in nutrients, so agents of degradation are mostly cellulolytic and ligninolytic fungi (Poleno et. al. 2009). Third variant represents well matured manure, which has very good biochemical and microbiological properties, including rich content of nutrients, therefore it´s persistence is caused by recalcitrant forms of organic compounds. Important measure of persistence could be also C/N ratio and N content of biomass (Horwath 2007).

One of the most important advantages of agroforestry systems is its SOC sequestration potential, which is significantly higher than in standard arable land. These practises can help recover C stock up to 35% of original forest soil values, lost by slash and burn management (Sanchez 2000). With sustainable management a large portion of organic carbon returns to the soil in the form of crop residues and leave litter (Sollins et. al. 2007). Estimation for average C storage capacity of AFS (up to 1 m soil depth) ranges from 30 to 300 t/ha, with annual sequestration potential from 0,29 to 15,21 t/ha (Ramachandran et. al. 2010). Global estimates for AFS over a 50-year period range between 1.1 and 2.2 Pg C year^{-1} but, in particular, estimates of land area are highly uncertain (Dixon 1995).

Pastures and meadow represents maybe the best way of land management from an environmental point of view. Grass and legumes make perfect cover, that protect soil against water and wind erosion. Root system is extremely dense and very deep (especially alfalfa) and provide large amount of organic material of good quality (Šantrůček et al. 2008), this amount of biomass is even higher than in a forest, although trees produce much more recalcitrant material (Jobbágy & Jackson 2001; Conant et. al. 2001). Specifically, root-derived C is more likely to be stabilized in the soil by physicochemical interactions with soil particles than shoot-derived C, residence time of root-derived C is approximately 2.4times that of shoot-derived (Rasse et. al. 2005). For example, the relative root contribution of European beech (*Fagus sylvatica* L.) to SOC was 1.55 times than that of shoots (Scheu & Schauermann 1994). Similarly, in croplands, total root-derived C contributed between 1.5 times to more than 3 times more C to SOC than shoot-derived C (Johnson et al. 2006).

3.2. AFS as a global warming mitigation strategy

One of the recognized causes of climate change is the increasing concentration of atmospheric carbon dioxide (CO_2). Since industrial revolution, CO_2 concentration has increased more than 40%, rising from 280 ppm in 1750 to about 392 ppm in 2012, in that year were emitted around 9,7 Pg of C (Peters et. al. 2013). It was expected to exceed

400 ppm by 2015 (Jose and Bardhan 2012). In the beginning of 2023 CO_2 concentration reached 420 ppm (co2.earth/daily-co2).

Carbon management is therefore a symptomatic phenomenon for climate change mitigation and proper maintenance of agricultural soils is irreplaceable tool for solution of this complex issue.

The scale of environmental problems, which are deeply connected with global agriculture is enormous, e. g. especially cattle livestock and rice production are responsible for circa 50 % of global anthropogenic emissions of CH_4, which is approximately 20 times stronger climate change agent than CO_2. Even worse is N_2O which is almost 300 times stronger (sic!) then CO_2 and agriculture is responsible for 70 % of total anthropogenic emission, due to nitrogen fertilization (Hutchinson et al. 2007; Vaněk et al. 2016). In contrast with these statistics, seems 25 % of whole CO_2 emissions caused by agriculture (Hutchinson et al. 2007) like not such a big deal, not to mention that calculation of carbon balance in this field (sensu lato) is apriori problematic because of the main purpose of agriculture, which is „transformation“ of CO_2 into plant production and that should automatically means positive environmental outcome.

Different point of view will provide absolute numbers. Due to land use changes since Industrial revolution were emitted 214 ± 67 Pg (petagrams) C. Contribution of SOC (Soil organic carbon) depletion to this amount is 78 ± 12 Pg, which could be assumed as basic estimation of soil carbon sink. Just for comparation, fossil fuel combustion, which is considered as main producer of (not just) CO_2 in atmosphere, make up 270 ± 30 Pg C (Lal 2004). These numbers are only fraction of whole soil carbon storage that reaches approximately 2 500 Pg (estimation of one-meter depth), but if we consider only cultivated land, it means lost of 50 – 70 % of soil C stocks (Lal 2004). Circa 1 500 Pg make up SOC, rest is C in carbonates, etc (Lal 2004). Despite their low carbon concentrations, subsoil horizons contribute to more than half of the global soil C stock (Jobbágy & Jackson 2000).

Although it is just rough assessment, these numbers could (and maybe should) be considered as potential threat.

This amount of SOC is also equivalent to 3,2 times size of atmospheric and 4 times of biotic C pools (Hutchinson et al. 2007; Fischlin et al. 2007). However, not all of emitted CO_2 accumulates in the atmosphere as land-based sinks take up significant amounts, i.e., about 28 % of anthropogenic CO_2 emissions were taken up on average between 2002 and 2011 (Peters et al. 2012).

The estimation for successful climate mitigation is global sequestration of 3,5 Pg C in soil per year (Zomer et al. 2017). It is expected that global croplands could store C for at least 20 years before reaching saturation points in North America and Europe (Sommer & Bossio 2014). In conclusion, land-based C sinks including those in agricultural ecosystems take up about one third of anthropogenic CO_2 emissions (Lorenz & Lal 2014).

Current values of SOC content vary from less than 100 t C/ha, that could be found across equatorial belt to more than 400 t C/ha, typical for peat soils in temperate and subarctic zones (Zomer et al. 2017). In tree-based land-use systems, soil accounts for 60% of total C storage (Lai 2004)

3.3. Role of carbon in soil

The first pioneer of soil research was probably Olivier de Serres, french agronomist from 16th centaury. His major work, Théâtre d'Agriculture is considered as the first scientific treatise about agriculture and soil, it was even inspiration for Physiocratism, maybe first highly developed economic theory, that consider soil and agriculture outcome as base source of national wealth (https://en.wikipedia.org/wiki/Olivier_de_Serres; https://en.wikipedia.org/wiki/Physiocracy 2023). The founder of pedology as independent scientific discipline, was geologist Vasily Dokuchaev, who described russian chernozem at the end of 19th centaury (https://en.wikipedia.org/wiki/Vasily_Dokuchaev 2023).

This historical intermezzo was important for illustrating this remarkable discrepancy between, apparently long-term knowledge of essential role of soil and relatively very short history of reliable scientific research. In author´s humble opinion is this matter of fact and also necessity of long-term research due to relative impossibility of estimation of soil biochemistry mechanisms based on experiments with limited samples, main reasons of still very shallow understanding of complex soil development, especially its organic part.

Present theories comprehend soil as complex, independent part of biosphere, or better said as natural intersection between bio-, lito-, hydro- and atmosphere. Sometimes even, in almost metaphysical way as integral living organism itself. Fact is, that mineral and organic part of pedosphere are inseparable and this “symbiosis” is crucial for every soil attribute, especially (and obviously for agriculturist) fertility.

Simply said, fertile soil is not necessarily a soil with plentiful of nutrients (nitrogen, phosphorus, potassium, calcium, etc.) but a soil with high capability of sorbing those elements. This characteristic depends on physical, biochemical a microbial condition which depends on many, mostly climatic and subsoil (i.e. geological) factors. However, these factors influence each other. Rich content of carbonates, which are important source of base, can be found in aridic or semi-aridic regime, on the contrary, very specific character of soils in tropical zone is (probably) primarily caused by extreme values of precipitation and high temperature, which influence every part and every process in soil, including chemical disintegration of minerals, specifically forms of iron and aluminium.

Favourable conditions for pedogenesis (*inter alia*) are:

- High variation of temperature, which cause bulk changes and significantly helps with processing of soil mass.

- Limited volume of precipitation, i.e. aridic or semi-aridic regime, which minimalize leak of soluble minerals and other nutrients from soil profile. Also, low rainfall (with unfavourable temperature condition) naturally regulates biomass growth in ecosystem, which most likely contribute to good SOC behaviour. Important details is character of rain water as weak carbonic acid, which means that intensity of precipitation represents simultaneously stabile form of stress for buffering capacity of soil (i.e. ability of systems to calibrate acid-base balance).

- Optimal (qualitatively and quantitatively) input of organic matter into soil. It seems, that ideal material for this purpose provide biomass (primarily roots) of grass and legumes species. Especially lucerne (alfalfa) can root into extreme depth of 10 meters. Beside others benefits, this means, that deeply stored nutrients, out of reach for the majority of plant species and soil organism, can be raised up to a higher horizons and deposited in dead biomass for later utilization.

- It´s obvious, that grass based (steppe) ecosystems are suitable environment for large ungulates. Products of digestion of large amount fibre biomass, which is typical for ruminants is probably important factor in favourable soil development.

- Basic condition for pedogenesis is, of course geological base. The most fertile soils on earth are located on loess subsoil.

The fixation of elements in soils is based on ions balance. Majority of soil particles have negative charge, which means that they interact with positively charged ions (cations) of nutrients. Capability of soil to bond and accumulate nutrients in a form, from which they can be subsequently released into soil solution is usually used as expression of soil fertility. It’s quantified by these parameters:

- Cation exchange capacity (CEC): (also *Maximum sorption capacity)* represents maximum possible amount of cations, that can be sorbed on whole soil particles surface. Its expressed in mmol of cations per kg (or 100 g) of soil.
- Total exchangeable bases (TEB): means sum of actually sorbet bases (calcium, magnesium, potassium, sodium). Expressed in similar way.
- Base saturation (BS): Rate of TEB to CEC, calculated in percentage.

The highest capability of cation sorption occurs in soil colloids. These are composed by secondary clay minerals (illite, monmorillonite) and stabile organic compounds, in favourable ratio. For optimal creating and stabilization of soil structure is necessary sufficient amount of Ca and Mg, which stabilize colloids and saturate buffer capacity, which keeps acid-base balance in suitable values.

There are two possible ways for C sequestration in soils

: (1) direct fixation of CO_2 into soil inorganic forms and

: (2) indirect fixation of C, through photosynthetic process into plant tissues, which are then decomposed and certain part of carbon, which vary depend on soil conditions and quality of material, stays in soil and the rest is released into atmosphere.

Global ratio of organic/inorganic soil C is cca 2/1 (Burras et al. 2001).

Prevailing scientific paradigm about SOC assume that the role of organic matter in soil is long-term, continuous process of decomposition and synthesis. Outcome of this cycle should be very persistent (so called recalcitrant) organic compounds, humic substances. This carbon macromolecules are:

- Fulvic acids: probably the youngest and the least recalcitrant humic compounds, soluble in mineral acids, lye and also in water. In composition of elements prevails carbon and oxygen. Water solutions are strongly acid (pH 2,6-2,8), thus very aggressive towards mineral part of soil, this could cause leaching of nutrients and colloids (Pospíšilová 2012)

- Humic acids: most valuable type of humic compounds with higher content of carbon and lesser content of oxygen. Humic acids are almost insoluble by water and are probably much older than fulvic acids (Vlček et al. 2020)

- Humins and humic coal: the oldest and extremely recalcitrant compounds with very high content of carbon. De facto insoluble and sensu stricto not a type of humic substances because of the fact that they are almost biologically inactive (Vlček et al. 2020).

An assumption about organic matter in soil is, that the more recalcitrant is organic tissue which will be decomposed, the higher is probability that the outcome of complicated soil chemistry and biology mechanisms will be humic compound of high quality and quantity (Šimek et al. 2019). But exact details of these processes are still very unclear. An extensive body of research has shown, that proper agricultural operations like addition of well matured manure of good quality, cover cropping, conservation tillage, periodic grazing or agroforestry practice can increase SOC stock (Bottcher & Garz 2000, Merbach & Deubell 2008, Paustian et al. 2016).

Organic matter in subsoil horizons is characterized by very long turnover times that increase with depth—radiocarbon ages of 1 000 to 10 000 years are common—but the reasons for this are not clear. Microbial activity may be reduced by suboptimal environmental conditions, nutrient limitation or energy scarcity and organic matter may be less accessible because of its sparse density or association with reactive mineral surfaces. Microbial biomass decreases with soil depth (Fierer et. al. 2003). Any disruption of the stabilization process may result in the decomposition of SOC even if its thousands of years old (Ewing et al. 2006).

The persistence of soil organic carbon is primarily not a molecular property, but an ecosystem property (Sanderman et. al. 2010). Organic matter persists not because of the intrinsic properties of the organic matter itself, but because of physicochemical and biological influences from the surrounding environment that reduce the probability (and therefore rate) of decomposition, thereby allowing the organic matter to persist (Schmidt et al. 2011).

However, it is necessary to say, that scientific view on role of carbon in soil chemistry is, especially in recent two decades, split into two prisms. Tradition point of view, which was described above comprehends SOC cycling as long-term process, which ends with stabile humic compounds as outcome (Šimek et al. 2019; Vlček et al. 2020; Totsche et. al. 2010). Limits of this theory are primarily, that observation of these complex microbiological processes in real time is (almost!) impossible.

Therefore the elementary question still remains unanswered: If organic matter is thermodynamically unstable, how is it possible for humic compounds to persist in soil, in some cases probably for thousands of years and still be able to participate in nutrient sorption and change, and interact with wide scale of life forms in soil (Hedges et al. 2000)?

Importance of the ‘recalcitrance’ of the input biomass and of humic substances is being questioned. New observations show these to be only marginally important for organic matter cycling (Marschner et al. 2008, Kleber & Johnson 2010). Contemporary theories perceive role of organic matter more like continuous way and deny existence of stable macromolecular substances as final product of biochemical synthesis. Origin of humic compounds is usually explained as result of, often very aggressive analytical methods, which are used in pedological research. The most stable forms of humus like humic coal can be isolated only by total chemical dissolution of those soil parts, on which are stable SOC compounds bonded (Šimek et al. 2019). Current techniques for direct, in-situ research are capable of non-destructive observation in high resolution. Conclusions based on these methods are, that functional group chemistry of extracted humic substances could be explained as relatively simple biomolecules, without the need to invoke the presence of unexplainable macromolecules (Kelleher & Simpson 2006). Humic substances were thought to contain large, complex macromolecules that are the largest and most stable SOM fraction, but with recent finding it seems, that these components represent only a small fraction of total organic matter (von Lutzow et al. 2006; Kleber & Johnson 2010; Schmidt et. al. 2011). Moreover, the chemical mixture of SOM is spatially distinct on a nanometre scale, and the aromatic/carboxylate-rich compounds, which are characteristic for the bulk extracted humic substances, have not been found in-situ even when looking at the submicrometric scale (using near-edge X-ray fine structure spectroscopy combined with scanning transmission X-ray microscopy) (Lehmann et al. 2008).

3.4. Consequences of land-use changes to AFS

Guo and Gifford (2002) found decreased SOC stocks after the conversion from pasture to plantation, native forest to crops, and pasture to crops. The meta-analysis indicates that soil C stocks decline after land use changes from:

- pasture to plantation (− 10%)
- native forest to plantation (− 13%)
- native forest to crop (− 42%)
- pasture to crop (− 59%).

Soil C stocks increase after land use changes from:

- native forest to pasture (+ 8%)
- crop to pasture (+ 19%)
- crop to plantation (+ 18%)
- and crop to secondary forest (+ 53%).

Wherever one of the land use changes decreased soil C, the reverse process usually increased soil carbon and *vice versa*. Broadleaf tree plantations placed onto prior native forest or pastures did not affect soil C stocks whereas pine plantations reduced soil C stocks by 12–15%

This trend was expected. Forests retain the most part of their SOC in the upper layers of soil and conversion from forest to agriculture caused loss in SOC, especially in topsoil. However, the effect of natural vegetation on SOC is less evident in deeper layers, where no significant changes in SOC stocks were observed in the land-use change from forest to agrisilviculture (0–60, 0–100, 0 ≥ 100 cm), and forest to agrosilvopasture (0–100 cm) (Guo and Gifford 2002).

Stefano & Jacobson 2017 published meta-analysis from 53 older studies about influence of land-use changes from various type of management to AFS:

- **0-15 cm**
  The conversion from agriculture to agroforestry showed increasing SOC stocks of 26 %. The conversion from forest to agroforestry indicated an opposite effect with a decrease of 26 %.
  No significant differences in SOC stocks were found in the shift from pasture/grassland/uncultivated to agroforestry. Removing natural forest and uncultivated land from the analysis produced a significant effect with a 13 % increase of SOC.
  Change from agriculture to agroforestry increased the SOC stocks by 25 %, while there was no difference in the conversion from agroforestry to pasture/grassland.
  Looking at specific agroforestry systems, significant differences on SOC stocks were detected in the transition from forest to agrisilviculture (12 % decrease), forest to

silvopasture (44 % decrease), and agriculture to agrisilviculture (25 % increase). Land-use change towards agroforestry showed a significant effect on SOC (9 % increase), when natural forest and uncultivated land were removed from the analysis.

- 0–30 cm
  Land-use change to agroforestry denoted a positive and significant effect size on SOC stocks, with an increase of 12 %. Other significant effect on SOC stocks were observed in the transition from forest to agroforestry (22 % decrease), pasture/grassland to agroforestry (9 % increase), agriculture to agroforestry (40 % increase), and uncultivated land to agroforestry (25 % increase).
  Significant differences on SOC stocks were detected in the transition from forest to agrisilviculture (24 % decrease), agriculture to agrisilviculture (40 % increase), pasture/grassland to agrosilvopastoral (13 % increase) and uncultivated land to agrisilviculture (55 % increase) and to agrosilvopastoral (7 % increase).

- 0–60 cm
  The conversion of pasture/grassland to agroforestry significantly increased SOC stocks by 10 %. On the other hand, the conversion of uncultivated land to agroforestry decreased SOC stocks by 23 %. No significant effect sizes on SOC stocks were found in the conversion from forest/forest plantation/agriculture to agroforestry.

  Significant changes in SOC stocks were reported in the conversion from forest plantation to silvopasture (17 % increase), forest to agrosilvopastoral (27 % decrease), agriculture to agrosilvopastoral (21 % increase), agriculture to silvopasture (66 % increase) and pasture/grassland to agrisilviculture (8 % increase).

- 0–100 cm
  The land-use change from agriculture to agroforestry significantly increased the SOC stocks by 34 %. On the other hand, there was no significant difference in the land-use change from forest/pasture/grassland/forest plantation/uncultivated land to agroforestry.

Specifically, significant decreases in SOC carbon were observed in the conversion from forest to agrisilviculture (0–15, 0–30 cm).

The conversion from forest to agroforestry lead to losses in SOC stocks in the top layers, while no significant differences were detected when deeper layers were included. On the other hand, the conversion from agriculture to agroforestry increased SOC stocks in most of the cases. Significant increases were also observed in the transition from pasture/grassland to agroforestry in the top layers, especially with the inclusion perennial in the systems, such as in silvopasture and agrosilvopastoral systems. Finally, the conversion from uncultivated land to agroforestry produced inconsistent results, perhaps due to the high variability of the category, and the little available land-use history. Overall, SOC stocks increased when land-use changed from less complex systems, such as agricultural systems (Stefano & Jacobson 2017).

Upson & Burgess (2013) concluded significant differences in SOC in the top 0.6 m of soil. Amount of C under the trees (161 t/ha) was greater than in the control (142 t/ha). There wasn´t found any trend in 1.5 m soil depth assessment. From a limited sample, there was no tree effect on the proportion of recalcitrant soil organic carbon. Size of SOC pool could normally vary from 1,25 t/ha in top 40 cm of 13-year-old alley cropping system in Southern Canada to 173 t/ha in 1 m depth of 16-year-old silvopastoral systems at the Atlantic Coast of Costa Rica (Amézquita et al. 2005; Oelbermann et al. 2006). Very high SOC pools of 302 t/ha to 100 cm depth have been reported for 30-year-old cacao agroforestry systems in Brazil (Gama-Rodrigues et al. 2010).

Shelterbelts had a significantly higher amount of SOC compared with adjacent agricultural fields, with an average difference of 18.6 t/ha in the top 50 cm soil, with another 3-8 t/ha in the tree litter layer. Younger shelterbelts (up to 20 years) tended to lose SOC in the early years of shelterbelt establishment, however, the SOC accrual was positively related to shelterbelt age. Besides stand age, other shelterbelt characteristics, including tree height and diameter, crown width, and amount of surface litter, were also positively correlated with the increase in SOC concentration (Dhillon & Van Rees 2016).

The heterogeneous nature of agroforestry in terms of site, soil type, tree species, and management practices, produced an inconsistent estimate of agroforestry C stocks (Montagnini and Nair 2004; Nair 2011, 2012). Nair (2011, 2012) have largely discussed about methodological discrepancies and issues related to soil sampling depth, preparation of samples, experimental design and calculation/presentation of results, pointing out the lack of rigorous standards. The lack of standardized methodologies certainly influences findings, in particular heterogeneity, which might bias outcomes (Borenstein et al. 2009). One way to deal with the problem is to include more precise and consistent studies: increasing the sample size increases precision and reduces the variation (Zlowodzki et al. 2007). Also, studies should include important explanatory variables, such as age of the systems and time to have C sequestration rates (quantity of C per area unit per time) rather than SOC stock quantities (Kim et al. 2016), adopted management practices (fertilization, irrigation, tillage, etc.), depth-relative BD, soil texture, pH, silt and clay content values (Brown and Lugo 1990; Laganiere et al. 2009), climatic factors (Brown and Lugo 1990); and vegetation species (Guo and Gifford 2002).

Materials and methods

3.5. Study sites

Fig. 1: Map of Czech Republic with marked research sites.

3.5.1. Průhonice

The first study site is comprised of the research plots established in experimental area Research institute for landscape and horticulture (VÚKOZ), which is located near Průhonice village. Year average temperature in a district is 8,5 °C, average precipitation around 570 mm. Altitude of the area is cca 290 m.

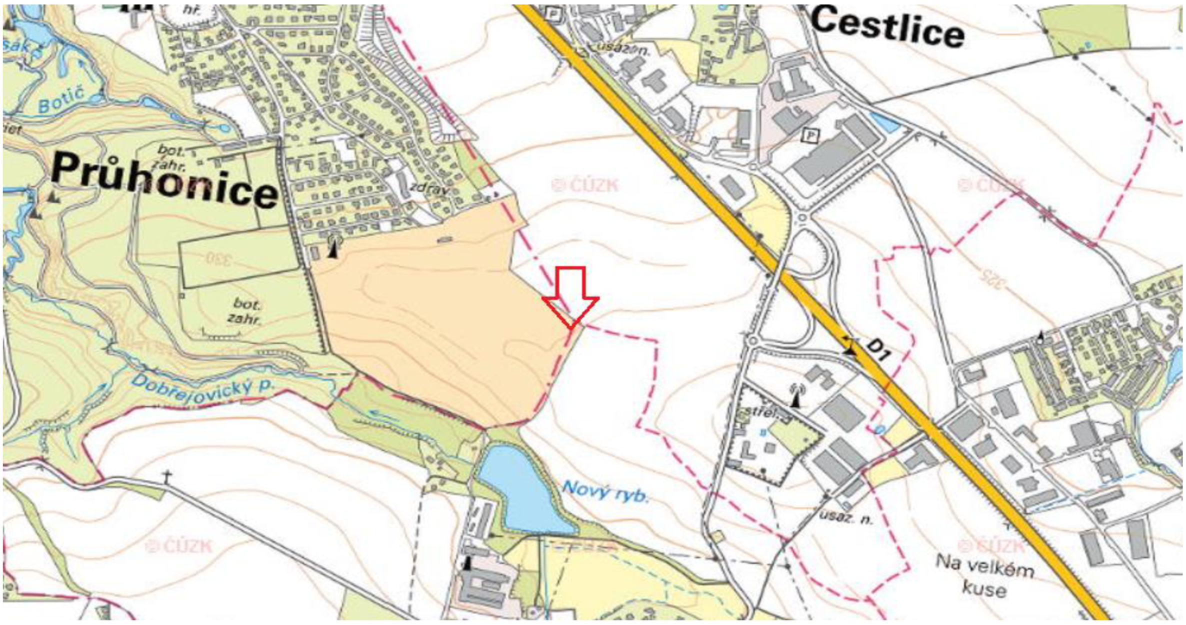


Fig. 2: Location of Průhonice area.

Experimental plot was established in 2018 from an old sapling nursery, where trees were removed to form arable alleys. The remaining trees are maple, rowan, lime and Turkish hazel. The alleys are managed by a local agricultural company identically as the surrounding agricultural areas.

3.5.2. Šardice

The second study site in situated in the South Moravian region, near Šardice village. Average temperature is 9,4 °C and average precipitation 561 mm. Altitude of area is around 190 m.

Research area is comprised of a arable field and grassed stripes of irregular width, with plum trees. The parcel has moderate slope with exposure to southwest. The tree alleys lead through the contours. Arable land and grassed parts are maintained by common agricultural methods.

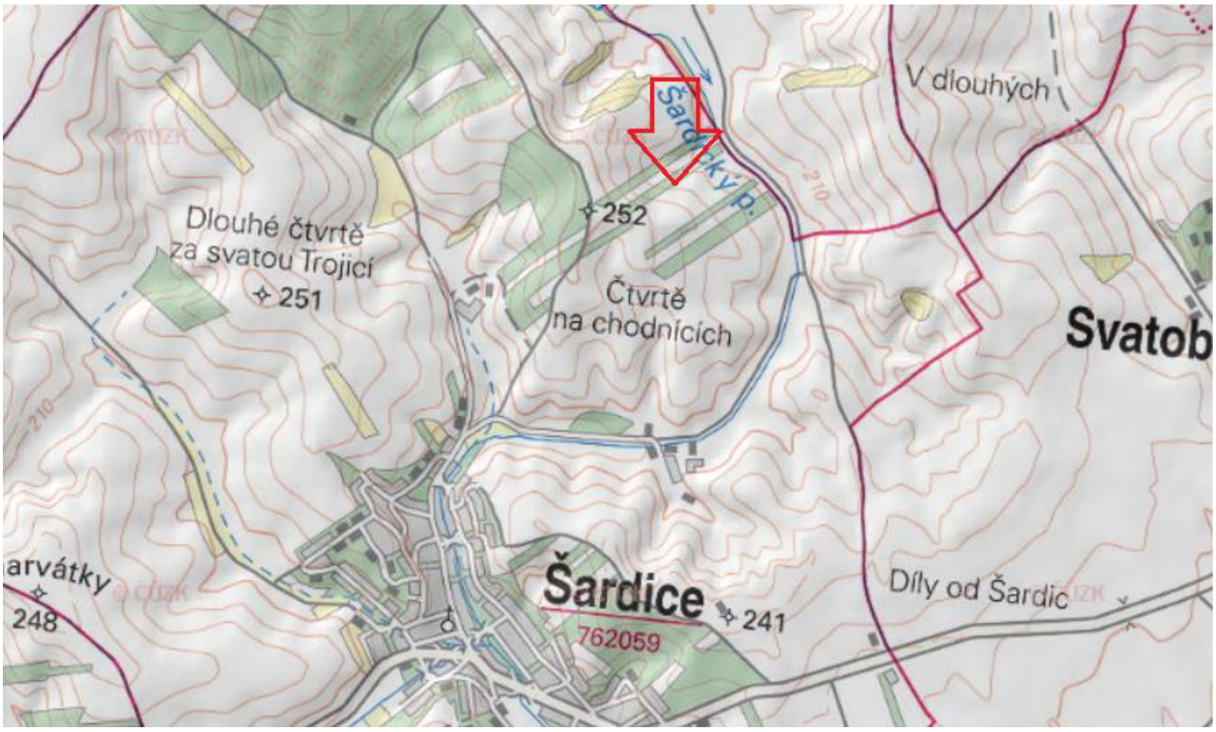


Fig. 3: Location of Šardice area.

3.6. 4.2. Experimental design

3.6.1. Průhonice

The AFS consists of four alleys, two of them are 15m wide and two are 10m wide. Samples were be collected along three transects in the AFS area as depicted in Fig 3. Additionally, six points were collected within the tree rows to obtain a total six repetitions. In total, 42 soil sampling points were selected in the AFS area.

Control samples were collected in the woodland (i.e. unmaintained tree nursery) area and in the adjacent conventional arable land, which has been managed equally as the AFS alleys since the AFS establishement. In total, there were 6 sampling points in woodland and 6 sampling points in arable land. Thus, we collected soil samples from 54 points as shown in the Fig 3.

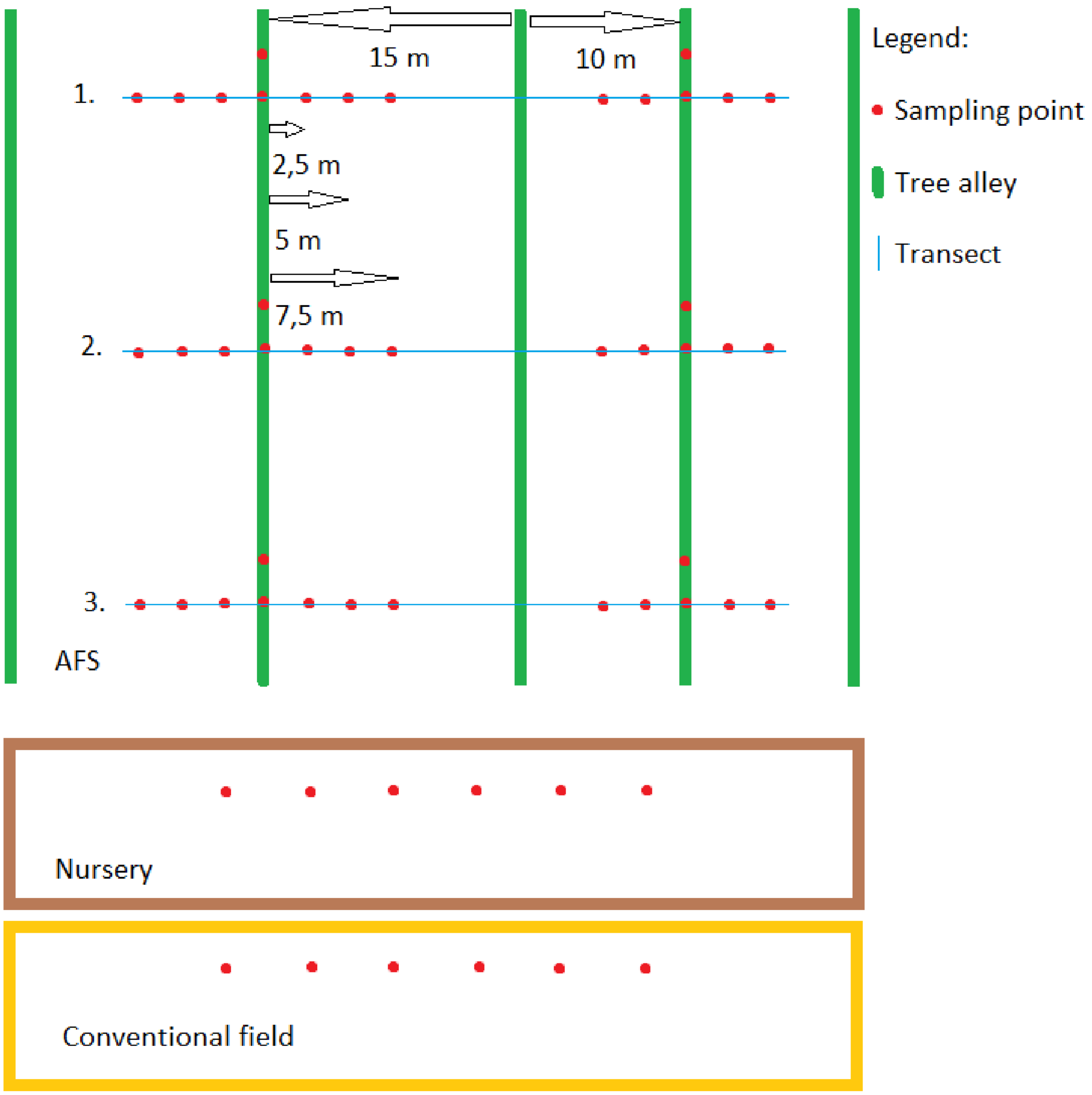


Fig. 4: Sampling scheme of Průhonice.

3.6.2. Šardice

The AFS consists of five alleys which differ in width (1 – 5 rows of trees). Samples were be collected along three transects in the AFS area as depicted in Fig 4. In total, 45 soil sampling points were selected in the AFS area, of which 9 are located in tree alley, 24 on grassed parts and 12 on arable soil.

Control samples, were collected (6x) from a middle of the field between tree alleys, which are in enough far distance, that influence of wood perennials is probably non-significant. Last set of samples (6x) were taken from the adjacent conventional arable land, which has been managed equally as the AFS alleys since the AFS establishement. Thus, in summary we collected soil samples from 57 points as shown in the Fig 4.

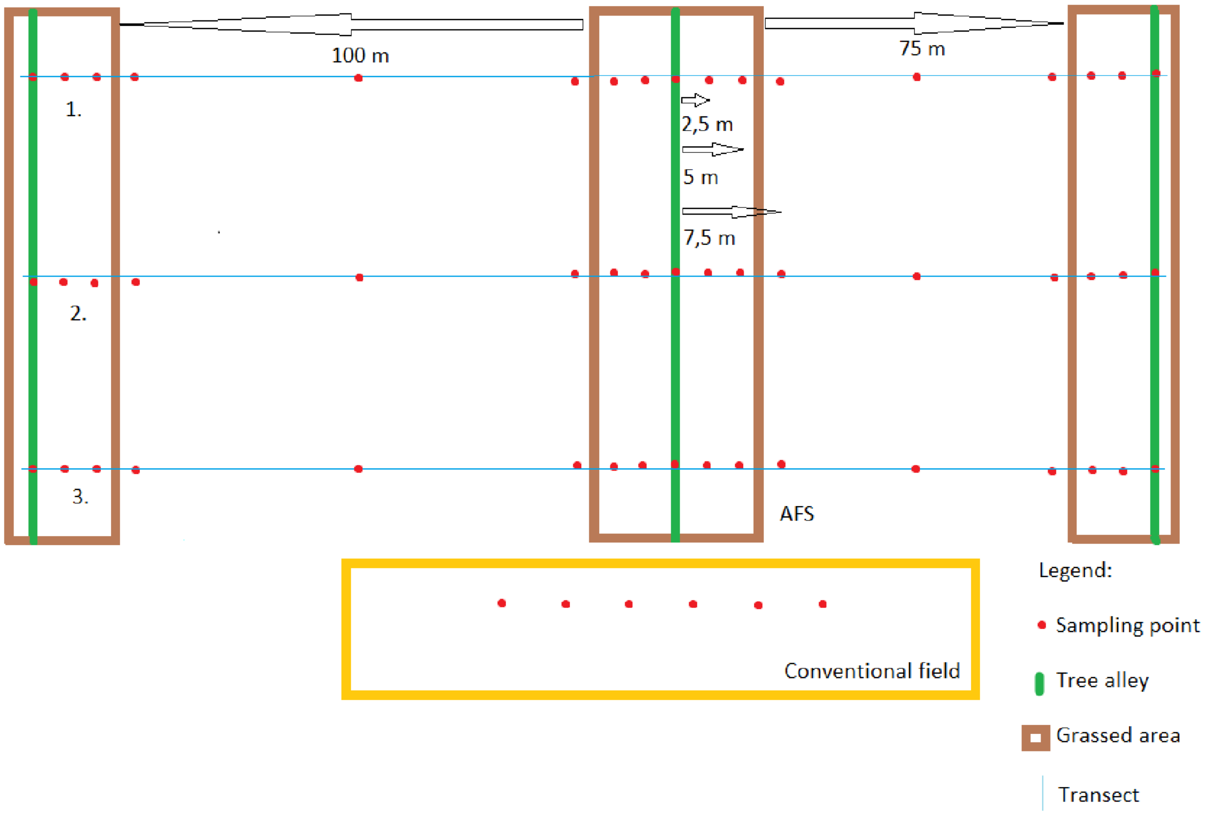


Fig. 5: Sampling scheme in Šardice.

3.7. Soil sampling

At each sampling point in both study sites, soil samples were collected from four depths:

- 0 - 10 cm
- 10 - 20 cm
- 20 - 40 cm
- 40 - 60 cm

Soil was stored in plastic bags, air-dried, sieved (<2mm) and stored at room temperature. A subsamples was then ball milled and used for the analysis of SOC.

3.8. Soil analysis

Soil pH was determined in 1 M KCl (1:2.5 soil-to-solution ratio) suspension after one hour of shaking.

Soil carbon was determined by thermic fractionation method.

4. Results

4.1. Průhonice

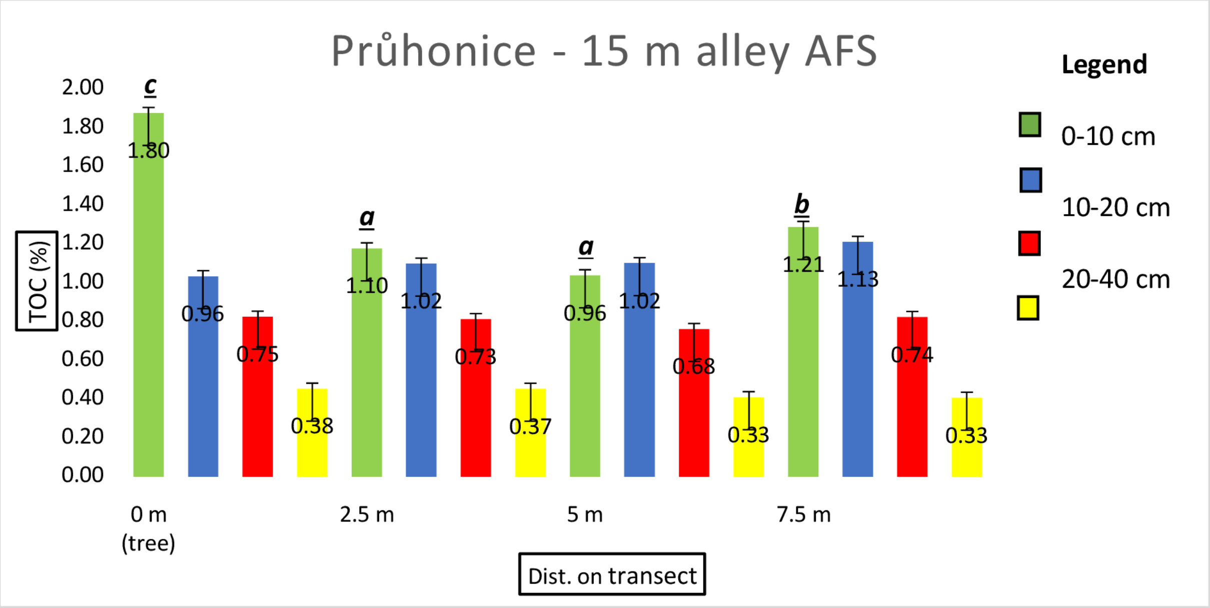


Fig. 6: Total organic carbon in Průhonice, part with 15 m distance between tree alleys. Comparison of samples collected from tree alleys and from 2,5 m; 5 m; 7,5 m distance from alley.

Only significant difference in SOC content was in top 10 cm of soil with the highest values at samples from tree alleys (***c***), much less difference (but still statistically valid) can be found at samples collected in 7.5 m (***b***) and 5 m (***a***) far from trees. Last sample in 2.5 m (***a, b***) far from alley, lies between them.

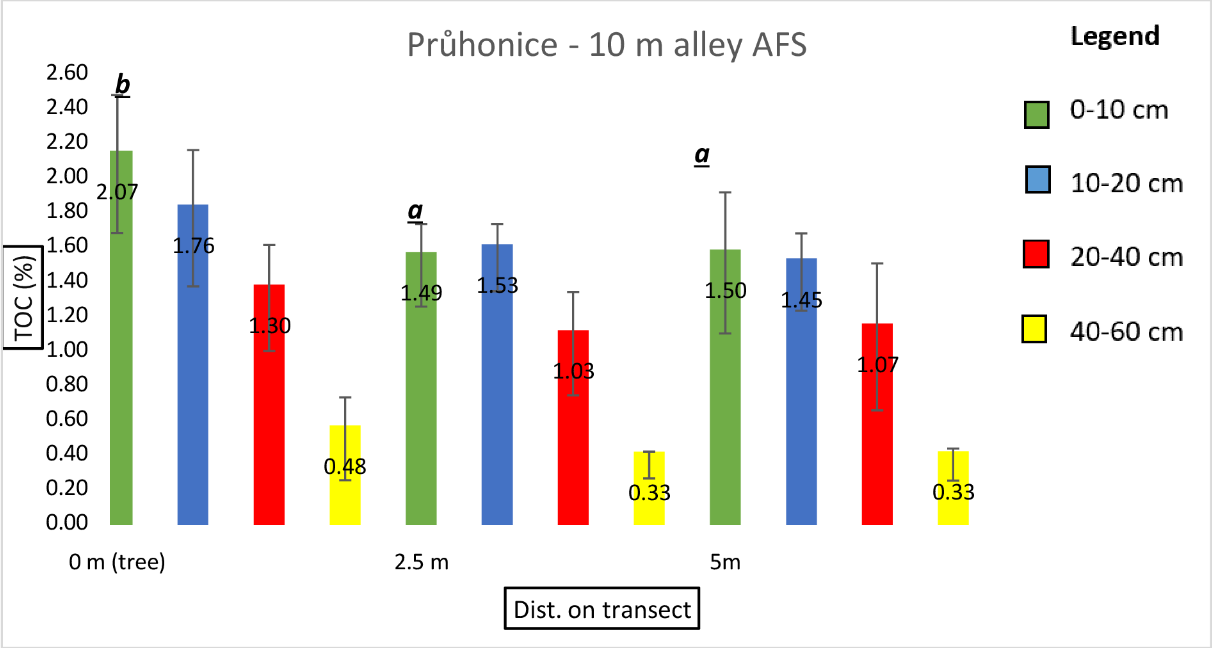


Fig. 7: Total organic carbon in Průhonice, part with 10 m distance between tree alleys. Comparison of samples collected from tree alleys and from 2,5 m and 5 m distance from alley.

Similar as previous chart, only significant variance was in top soil layer, with the highest SOC values under tree rows again (***b***). Rest of sampling layer was almost identical (**a**).

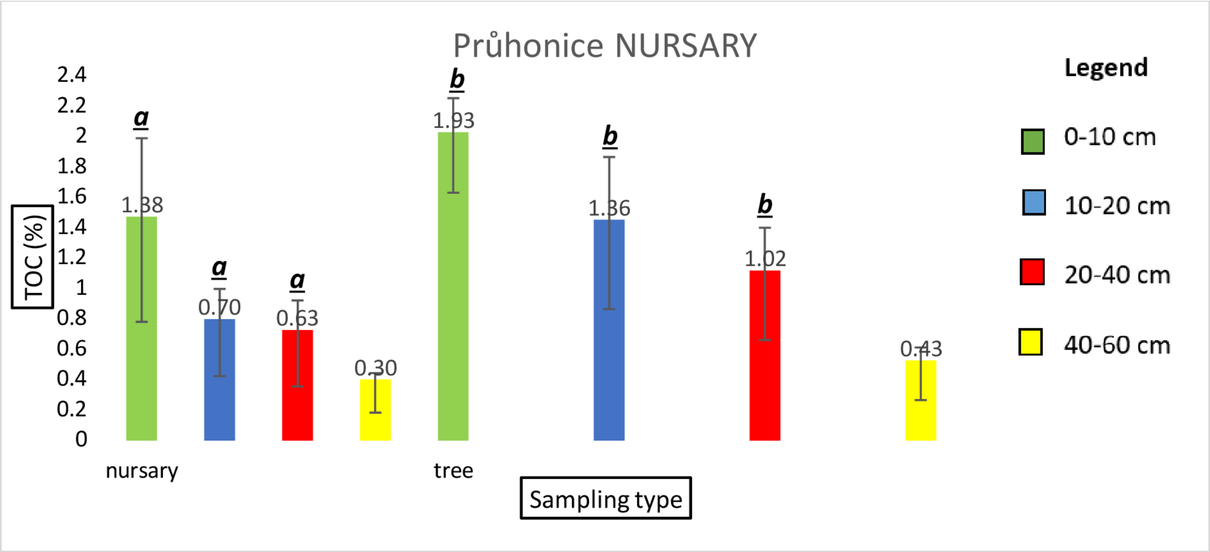


Fig. 8: Total organic carbon in Průhonice, compare of tree alleys with a woody fallow.

The comparison of samples from tree alleys and from old nursery, which could be seen as old woody fallow shows significantly higher values at tree rows in AFS (***b***) in top three sampling layers.

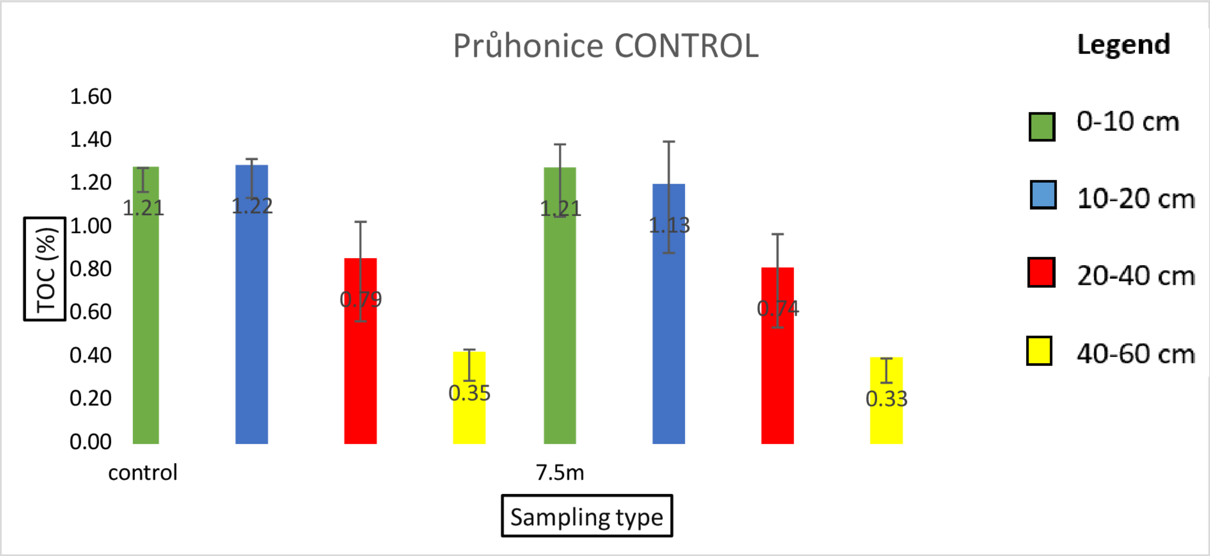


Fig. 9: Total organic carbon in Průhonice, compare of 7.5 m samples with control set from conventional field.

This comparison was without any significant variance.

4.2. Šardice

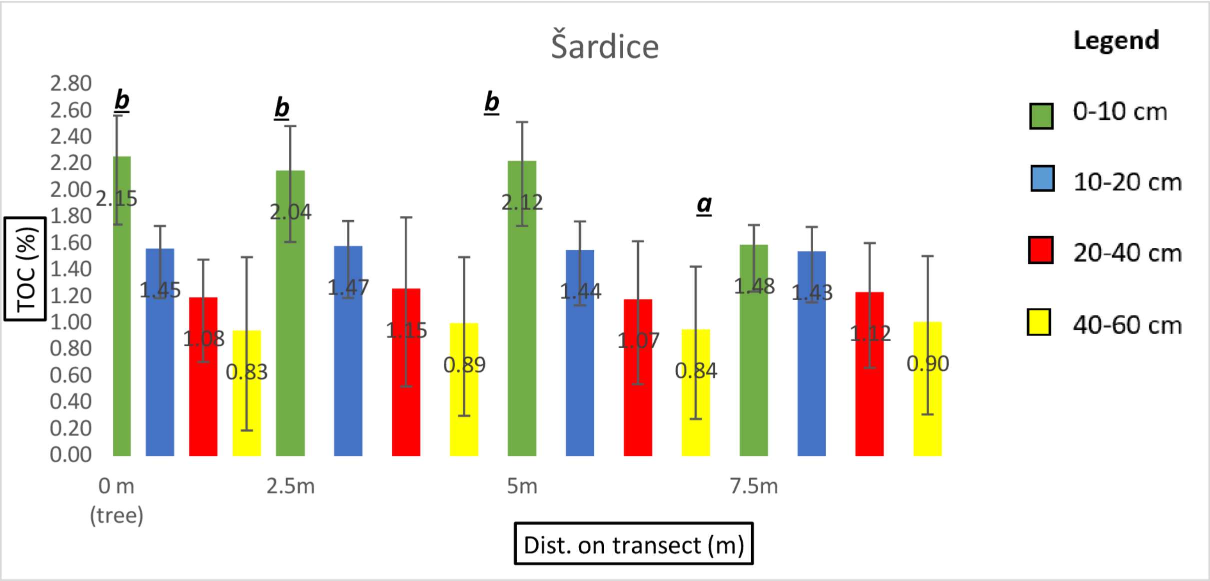


Fig. 10: Total organic carbon in Šardice, comparison of samples collected from tree alleys and from 2,5 m; 5 m; 7,5 m distance from alley.

On Šardice site were also only significant differences in top layer of soil, with the higher value in samples from under the tree alleys (***b***). Only a little lower were contents in 2.5 m and 7.5 m (***b***) distance and most significant drop can be seen in 7,5 m (***a***) sample.

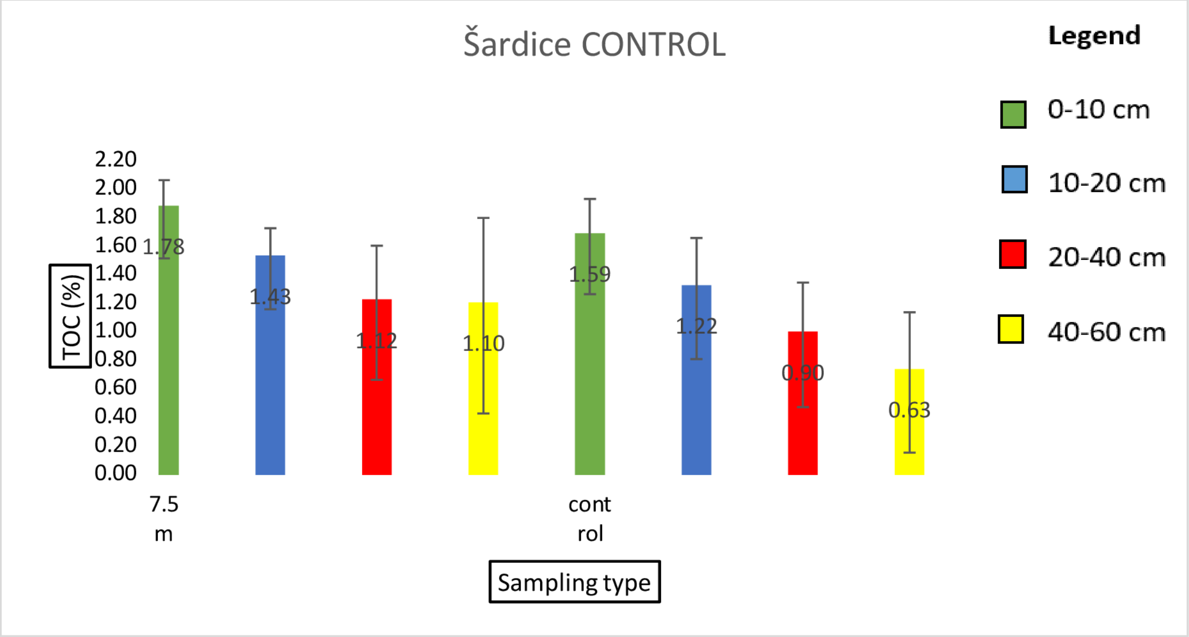


Fig. 11: Total organic carbon in Šardice, compare of 7.5 m samples with control set from conventional field.

Also in Šardice site were control samples without significant difference.

5. Discussion

With only single exception (which I comment later) significant changes were detected in a top soil horizon. This could be caused by several factors. The simplest explanation is relative short period of "afforestation", in both cases, AFS were established approximately 15 years ago, which could be relatively short period for considerable biomass accumulation, especially root biomass, with its high persistence and long turnover period (Cusack et al. 2009). Also, amount of aboveground litter, which tree can produce rise with increment in active biomass, i.e. bigger tree crown leads to bigger production of leaves, fruit or dead branches, that became carbon input into soil.

Similar argument is, that every changes in soil development are very slow and any increasing of organic compounds in horizontal or vertical direction from source of biomass is long-term process, which takes, at least decades (Šimek et al. 2019, Taylor et al. 2002)).

With increasing depth should rise influence of root biomass compared to grass roots. This trend wasn't found at all. Role of legumes crops taken into consideration. Alfalfa is characteristic by impressively rich and deep root system, which can grow to depth over 6 meters. These crops are commonly used in Central Europe on arable land, pastures and meadows (Šantrůček et al. 2008).

Generally, agricultural soil can be consider as favourable for trees but conditions typical for arable land (Vacek et al. 2009) like open exposure to the wind, lower humidity (at least periodically) or higher temperature fluctuations than in forest (or just any more heterogenous environment) may be limited factors for vegetation, which could be possibly seen on deficient root growth .

The Šardice area is quite atypical with large distances between tree alley of 100, resp. 75 m. Its questionable to what extent we can talk about the system, if distance from one point in arable land, to a nearest tree can be fifty meters. Part of CONTROL samples were therefore collected from the middle of arable parts of ASF.

Only significant difference in Šardice represent samples from 7.5 m distance. The key factor in this case in probably not a distance from tree but its location on arable land. Rest of samples in the set were collected from permanently grassed line, on which were tree alley established. So the main reason of variance is probably a high capability of grassland to accumulate SOC (Šantrůček et al. 2008) on the one hand and the impact of agronomic practises like tillage on the other. Agricultural practises, which contain mechanical processing of soil are considered as one of the main causes of SOC losses (Vlček et al. 2020).

Similar interpretation can be used in Průhonice, with most significant difference from tree alley. Alley itself is covered by grass, which is only provisionally maintained by brush cutter.

Only comparison with significant variance in deeper soil layers was between tree alleys and NURSARY, with higher content of carbon in AFS. This is quite surprise because trees in NURSARY was noticeably higher if compared with AFS. Explanation can be much denser canopy, which leads to strong limitation of light for ground herbs, which leads to limitation in SOC accumulation in this part (Svoboda 1952).

The meta-analysis (Guo and Gifford 2002) showed average increasing of SOC stocks 26% after conversion from agriculture to agroforestry, in first 15 cm layer of soil. This is similar to values from comparison between tree alleys samples and samples from various distance from alleys (Fig. 7., 10.). In Fig. 6. is increasing even higher.

Study from 2021 (Udawatta et al. 2021) compared soil under different regime of management. Row crop field contain 1.94 % SOC in top 10 cm layer, Agroforestry buffers contain 2.19 % and Grassed buffer 2.41 %. These data support assumption, that grass cover has so high ability to sequestrate carbon, that additive influence of trees can be negligible.

Can be discussed if increasement in one property (like SOC content) of single landscape element (which is possible point of view about any limited woody vegetation polygon in agricultural space) is truly quantifiable increasement of whole system.

The biggest obstacle is definitely strong heterogeneity of AFS. Any comparison of studies is usually indefinite a can be misleading because of plenty of variable, which must be included into assessment.

6. Conclusion

There was found significantly higher values of SOC content in top 10 cm layer in tree alleys in comparison with rest of AFS systems.

In comparison between conventional field and AFS samples in the longest distance from alleys wasn’t found any significant trend.

Outcome of comparison between tree alley and woody fallow was higher values for AFS.

Hypothesis, that woody perennials increase SOC in top soil layer can´t be rejected.

Hypothesis about SOC increasement in deeper soil layers can´t be confirm.

Hypothesis about SOC reduction with increasing distance from trees can´t be rejected.

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